

PSR J1141–6545: a powerful laboratory of GR and tensor-scalar theories of gravity

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Pulsars in close binary systems have provided some of the most stringent tests of strong-field gravity to date. The pulsar–white-dwarf binary system J1141–6545 is specifically interesting due to its gravitational asymmetry, which makes it one of the most powerful probes of tensor-scalar theories of gravity. We give an overview of current gravitational tests provided by the J1141–6545 binary system and comment on how anomalous accelerations, geodetic precession and timing instabilities may be prevented from limiting future tests of gravity to come from this system.

Keywords: pulsars; tensor-scalar theories

1. The J1141–6545 Binary System

PSR J1141–6545 is a common neutron star (pulse period $P \approx 394$ ms; spindown $\dot{P} \approx 4 \times 10^{-15}$) in a tight and slightly eccentric orbit around a heavy white-dwarf companion^{1,2} (orbital period $P_b \approx 4.7$ hr; $e \approx 0.17$). Its orbit is close to edge-on³ ($i = 76^\circ$) and its spatial velocity is expected to be high^{2,3} ($V \approx 115$ km/s).

2. Overview of Gravitational Tests

Because of the high companion mass, short orbital period and non-zero eccentricity of the system, three relativistic effects have been readily observed in the PSR J1141–6545 system.^{4,5} These three effects are the periastron advance⁵ $\dot{\omega} = 5.3096 \pm 0.0004^\circ \text{yr}^{-1}$, the gravitational redshift⁵ $\gamma = (7.73 \pm 0.11) \times 10^{-4}$ ms and the orbital decay caused by gravitational wave emission⁵ $\dot{P}_b = (-4.03 \pm 0.25) \times 10^{-13}$. All three of these effects only depend on Keplerian parameters that can be measured independently and on the masses of the pulsar and the white-dwarf companion (M_{PSR} and M_c respectively). This implies that the two most precisely measured effects can be used to uniquely define the system by requiring $M_{\text{PSR}} = 1.27 \pm 0.01 M_\odot$ and $M_c = 1.02 \pm 0.01 M_\odot$. Using these values to predict \dot{P}_b^{GR} and subsequent comparison with the measured value, provides a test of general relativity (GR). Since GR requires the inclination angle derived from the Shapiro delay “shape” parameter to equate to that derived from the component masses and orbital period, the orbital inclination angle derived from scintillation studies³ can also be used to test GR. As described by Bhat et al.,⁵ GR passes both these tests without problem.

The J1141–6545 system is furthermore particularly powerful in constraining tensor-scalar theories of gravity since these theories predict significant dipolar gravitational wave emission because of the different self-gravity of the pulsar and companion star.⁶ Specifically, in the regime of strong quadrature coupling ($\beta_0 \gg 0$), timing of PSR J1141–6545 currently places the strongest bound on the linear coupling constant: $\alpha_0^2 < 3.4 \times 10^{-6}$. At smaller values of β_0 , its current bound is only about a factor of three less constraining than the bound placed by laser ranging to the Cassini spacecraft.⁷ Since the parameters derived from timing become progressively more precise with a longer timing baseline, the limits from PSR J1141–6545 are expected to improve on the Cassini values by the middle of this decade.⁵ In the following section we will comment on the effects that may constrain these efforts.

3. Challenges in the J1141–6545 System

There are three effects that could pose serious constraints on future tests of gravity derived from timing PSR J1141–6545. These are anomalous accelerations of the system, geodetic precession and glitches, as detailed below.

3.1. Anomalous Accelerations of the System

Any apparent acceleration of the binary system will cause periodicities to change as a function of time, and will hence affect the measured orbital period derivative as well. Specifically, two contaminating factors may prove important. First the Galactic acceleration, both perpendicular to the Galactic plane (caused by the Galactic gravitational potential) and within the plane (caused by differential Galactic rotation). This effect mainly depend on the distance of the pulsar, which has been determined⁸ to be larger than 3.7 kpc. Based on that distance limit, the combined Galactic contribution to \dot{P}_b is expected to be at most -5×10^{-15} . The other contaminant is the Shklovskii effect,⁹ which depends on both the transverse velocity V_T and the distance D : $\dot{P}_b^{\text{Shk}} = \frac{V_T^2 P_b}{Dc}$. Assuming a distance of 3.7 kpc and a transverse velocity³ of 115 km/s, this effect is expected to be at most of the order of 7×10^{-15} . When compared to the current measurement precision on the orbital period derivative: $\dot{P}_b = -4.03 \pm 0.25 \times 10^{-13}$, it is clear that these contaminations are still well within the precision of our measurement and have therefore been inconsequential so far. Accurate determination of these effects will be required, however, to correct \dot{P}_b at the 2% level, a precision that should be reached by the middle of this decade. In order to enable such a correction, VLBI observations have been proposed to place a stronger limit on the distance and attempt an initial measurement of the proper motion.

3.2. Geodetic Precession

PSR J1141–6545 is known to exhibit geodetic precession.^{10,11} This effect causes changes in pulse shape which in turn affect the timing since it biases the cross-correlation of the pulse with a standard template. Extensive modelling of the pulse

shape and its evolution¹¹ provides a potential correction for this effect, because the time-evolving model of the pulse profile could be used as the basis to time the observations against. If successful, these efforts could severely decrease the effect geodetic precession has on the timing results.

3.3. Glitch and Timing Noise

Between 19 May and 15 July 2007 PSR J1141–6545 experienced a sudden spin-up otherwise known as a glitch.¹¹ Since pulsar glitches are poorly understood and because there does not exist a general and complete model of the timing effects of pulsar glitches,¹² ongoing monitoring is required to accurately correct the glitch and its relaxation process. While this does decrease the timing precision temporarily as the glitch model is improved towards its final solution, it is not expected to have lasting effect on the timing solution. The presence of this glitch does, however, suggest that earlier timing irregularities may also have been caused by an unmodelled glitch that occurred near the time when the pulsar was first discovered. Further investigations into this possibility may retroactively improve the precision of the timing solution for PSR J1141–6545.

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